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Synchronization transitions induced by the fluctuation of adaptive coupling strength in delayed Newman–Watts neuronal networks

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ABSTRACT

Introducing adaptive coupling in delayed neuronal networks and regulating the dissipative parameter (DP) of adaptive coupling by noise, we study the effect of fluctuations of the changing rate of adaptive coupling on the synchronization of the neuronal networks. It is found that time delay can induce synchronization transitions for intermediate DP values, and the synchronization transitions become strongest when DP is optimal. As the intensity of DP noise is varied, the neurons can also exhibit synchronization transitions, and the phenomenon is delay-dependent and is enhanced for certain time delays. Moreover, the synchronization transitions change with the change of DP and become strongest when DP is optimal. These results show that randomly changing adaptive coupling can considerably change the synchronization of the neuronal networks, and hence could play a crucial role in the information processing and transmission in neural systems.

1. Introduction

Synchronous processes are ubiquitous in nature and play very important roles in various fields ranging from physics to ecology, sociology, biology, and so on (Arenas et al., 2008; Suykens and Osipov, 2008). In neuronal systems, synchronous activity is of great significance in the information processing in the brain (Gray and Singer, 1989; Mehta et al., 2001; Bazhenov et al., 2001), but it is not desirable for several neurological diseases such as epilepsy and tremor in Parkinson's disease (Levy et al., 2000; Mormann et al., 2003). In recent years, many novel synchronization phenomena have been found, such as burst synchronization in an array of coupled neurons (Bahar, 2004; Wang et al., 2007a); gap-junction-enhanced synchronization in coupled bursting neurons (Yoshioka, 2005); burst synchronization in a small-world neuronal network (Zheng and Lu, 2008); diffusive coupling-enhanced synchronization in small-world network of spiking neurons (Hasegawa, 2005); subthreshold stimulus-enhanced synchronization in a square lattice noisy neuronal network (Wang et al., 2007b); noise-induced synchronization in excitable media (Neiman et al., 1999), coupled neurons (Zhou and Kurths, 2003), human-brain (Kitajo et al., 2007), and neuronal networks (Perc, 2009). Information transmission delays are inherent in neural systems due to the finite propagation speeds and time lapses occurring by both dendritic and synaptic processing (Kandel et al., 1991). Physiological experiments have revealed that the transmission delay introduced by chemical and electrical synapses can be several tenths of milliseconds and about 0.05 ms in length, respectively (Mann, 1981; Izhikevich, 2006). In the past years, there are many studies on the effect of time delay on the synchronization of neuronal systems, and many synchronization phenomena induced by time delay have been found in coupled neurons and neuronal networks (Wang et al., 2011a; Dhamala et al., 2004; Rossoni et al., 2005; Roxin et al., 2005; Ko and Ermentrout, 2007; Burić et al., 2008; Adhikari et al., 2011). Recently, a novel phenomenon of synchronization transitions has gained increasing attention, and many phenomena induced by neuronal coupling (Hao et al., 2011; Sun et al., 2011; Xu et al., 2013) and time delay (Wang et al., 2008a, 2008b, 2009, 2010, 2011b; Hao et al., 2011; Guo et al., 2012) and noise (Wu et al., 2014) have been found in various neuronal networks.

Neural network is adaptive, and the firing dynamics of adaptive neural networks has been extensively studied in the past decades. About nine years ago, Huang (2006) proposed a type of adaptive mechanism, which suggests that the coupling of oscillators on networks that have a larger difference grows stronger. With this adaptive mechanism, the synchronization of the oscillators increases with time. Adaptive coupling proposed by Huang involves a dissipative parameter (DP) that controls the changing rate of

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coupling strength. Studies have shown that adaptive coupling by Huang has a big effect on the temporal coherence and spatial synchronization of complex networks, for example, it can improve synchronization and is more efficient for the onset of synchronization as compared with the case for fixed coupling (Huang, 2006; Zhu et al., 2010), stochastic resonance occurs in adaptive small-world oscillator networks when DP is large enough (Wu et al., 2011), and coherence resonance occurs in Newman–Watts (NW) neuronal networks when DP is varied (Gong et al., 2013). More interestingly, synchronization transitions can occur in NW neuronal networks when DP periodically changes (Wang et al., 2013).

In these studies, however, the DP of adaptive coupling is always assumed to be deterministic. In fact, neurons are noisy elements, and noise arises from stochastic processes occurring in external stimulus, synapses and ion channels. Under the regulation of noise, there could be fluctuations in the DP of adaptive coupling, which will affect the changing rate of coupling strength. Therefore, it is of significance to study the effect of randomly changing DP on the synchronization of adaptive neuronal networks.

In this paper, employing adaptive coupling proposed by Huang in delayed NW networks of Hodgkin–Huxley (HH) neurons, we study how the fluctuations of the DP of adaptive coupling influence the synchronization of the neuronal networks. We first study how time delay induces synchronization transitions when DP is fixed, and then by regulating DP by noise, we study how the fluctuations of DP induce synchronization transitions. Finally, mechanisms are briefly discussed and results are concluded.

2. Model and equations

The dynamics of the membrane potential of a single HH neuron is given by:

$$C\frac{dV}{dt} = -g_{\mathrm{Na}}m^3h(V - V_{\mathrm{Na}}) - g_{\mathrm{K}}n^4(V - V_{\mathrm{K}}) - g_{\mathrm{L}}(V - V_{\mathrm{L}}) + \xi(t), \quad (1)$$

where $C = 1\,\mu\mathrm{F\,cm^{-2}}$ is the membrane capacity; $g_{\mathrm{Na}} = 120\,\mathrm{mS\,cm^{-2}}$ and $g_{\mathrm{K}} = 36\,\mathrm{mS\,cm^{-2}}$ are maximal sodium and potassium conductance, and $g_{\mathrm{L}} = 0.3\,\mathrm{mS\,cm^{-2}}$ is leakage conductance; $V_{\mathrm{Na}} = 50\,\mathrm{mV}$, $V_{\mathrm{K}} = -77\,\mathrm{mV}$ and $V_{\mathrm{L}} = -54.4\,\mathrm{mV}$ are the reversal potentials for the sodium, potassium and leakage currents, respectively. Gating variables m, h, and n governing the stochastic dynamics of sodium and potassium channels obey the equations:

$$\frac{dm}{dt} = \alpha_m(V)(1 - m) - \beta_m(V)m, \quad (2a)$$

$$\frac{dh}{dt} = \alpha_h(V)(1 - h) - \beta_h(V)h, \quad (2b)$$

$$\frac{dn}{dt} = \alpha_n(V)(1 - n) - \beta_n(V)n, \quad (2c)$$

with opening–closing transition rates:

$$\alpha_m(V) = \frac{0.1(V + 40)}{1 - \exp[-(V + 40)/10]}, \quad (3a)$$

$$\beta_m(V) = 4\exp\left[\frac{-(V + 65)}{18}\right], \quad (3b)$$

$$\alpha_h(V) = 0.07\exp\left[\frac{-(V + 65)}{20}\right], \quad (3c)$$

$$\beta_h(V) = \left\{1 + \exp\left[\frac{-(V + 35)}{10}\right]\right\}^{-1}, \quad (3d)$$

$$\alpha_n(V) = \frac{0.01(V + 55)}{1 - \exp[-(V + 55)/10]}, \quad (3e)$$

$$\beta_n(V) = 0.125\exp\left[\frac{-(V + 65)}{80}\right]. \quad (3f)$$

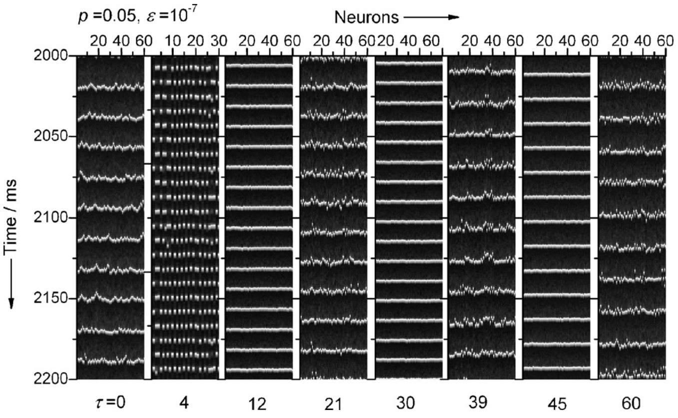

Fig. 1. Spatiotemporal patterns of the membrane potentials for different τ values at $\varepsilon = 10^{-7}$. The neurons intermittently become synchronous and non-synchronous as τ is increased, exhibiting synchronization transitions.

According to NW topology (Newman and Watts, 1999), the present network comprising $N = 60$ neurons starts with a regular ring, each neuron having two nearest neighbors, and then links are randomly added between non-nearest vertices. In the limit case that all neurons are coupled to each other, the network contains $N(N - 1)/2$ edges. Using M to denote the number of added shortcuts, the fraction of shortcuts is given by $p = M/[N(N - 1)/2]$, which is used to characterize the randomness of the network. For $p = 0$, the network is a regular ring; for $0 < p < 1$, NW small-world network occurs; for $p = 1$, the network is a globally coupled random network. Note that there are a lot of network realizations for a given p.

The dynamics of NW HH neuron networks with delayed electrical coupling is given by:

$$C\frac{dV_i}{dt} = -g_{\mathrm{Na}}m_i^3h_i(V_i - V_{\mathrm{Na}}) - g_{\mathrm{K}}n_i^4(V_i - V_K) - g_{\mathrm{L}}(V_i - V_L) + \sum_j \lambda_{ij}[V_j(t - \tau) - V_i(t)] + \xi_i(t) \quad (4a)$$

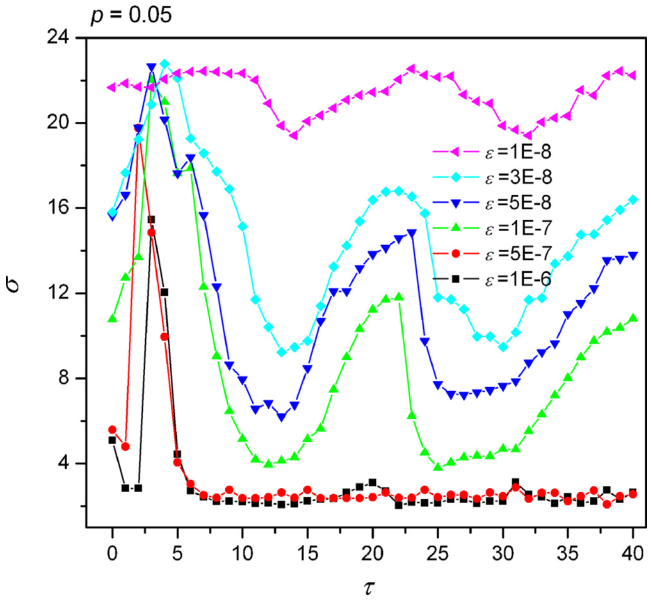

Fig. 2. σ in dependence on τ for diferent ε values. For too small or too large ε, σ passes through a few low peaks as τ increases; however, for intermediate ε, there are a few high σ peaks. This shows that delay-induced synchronization transitions occur and are enhanced when DP is intermediate.